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ESTIMATES OF REGIONAL ET FROM HCMM DATA :

SUMMARY OF 1977 EXPERIMENT AND FINAL ARRANGEMENT

FOR 1978 IN SOUTHEASTERN FRANCE TEST SITE

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I. DEFINITION OF THE PRECISE MAIN OBJECTIVE FOR HCMM DATA USE

11. Interest of regional ET

Potential ET, which may be considered as a climatic parameter, may be estimated within a 10 % accuracy limit at the scale of meteorological network.

On the contrary, actual ET is generally unknown, except for very large areas and long-time scales (by derivation of hydrological budgets) or some ponctual basins or fields where specific instrumentation is used.

Yet, the knowledge of actual ET at a regional scale (e.g for 10 to 10^4 km^2, depending upon the homogeneity of concerned surfaces) would be of great interest for either climatological (effect on evaporation on local climate), hydrological (significance of evaporation as a major component of water balance) or agronomic (effect of water availability on final yields as expressed by the ET/PET index) purposes.

12. Specific features of remote sensing data for regional ET

Large area global ET may be approached by various methods (atmospheric water vapour budget, planetary boundary layer equations for determination of atmospheric fluxes, use of relationships between regional evaporation and local measured potential evaporation,....).

But these methods

1) do not give precise informations about space repartition of evaporation since they directly derive the global large-scale value

2) by all ways are still research studies and cannot be thought to be operative within some years.

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Which appears the most useful procedure for the various climatological hydrological and agronomic purposes consists in determining small-scale homogeneous surfaces local ET then calculating global regional ET for the whole studied surface S as

$$ET = \frac{1}{S} \Sigma ET_i \times S_i$$

ET_i and S_i being the evaporation and surfaces of the contributing homogeneous small scale elements.

That approach may be performed by using water balance models, based on a regional value of PET and small-scale mapping of both main type of vegetative cover and soil water storage capacity. The corresponding procedure is however by far less attractive and promising than the use of remote sensing data, whose time and space scales are well adapted to the above defined requirements.

13. HCMM data use for estimates of regional ET in Southeastern France

As remote sensing use for estimating ET corresponds, at the present time, to a research study stage and not to an operational one, it was considered that objectives had to be limited to a reduced well-defined subject

a) in order to avoid complex problems of topography, only flat land will be first concerned, which concentrates the interest in the lower Rhone valley area.

b) as tall vegetative canopies (like wheat, corn...) or incomplete covering cultures (like fruit trees, vines...) arise specific problems for the definition and significance of infrared temperatures, it was decided to start work with the most simple model of short grass whose energy budget has been studied from some years in Avignon.

c) high contrasts concerning water availability seem to ensure greater working possibilites for that research by giving larger variation ranges of measured parameters.

These three considerations led to the decision of concentrate mean study interest, at least in a first stage, on a limited surface corresponding to the "Crau" plain on the east of Rhone delta.

It is a flat land, of about 50 km x 50 km, with a typical dryland grass as natural vegetative cover and large well-watered irrigated parcels in some places.

Before starting 1978 experiment in that region, preliminary studies were performed during 1977 summer on the experiment field in Avignon-Montfavet (which is located some 30 km north of the Crau plain).

II. MAIN RESULTS OF 1977 EXPERIMENT IN AVIGNON-MONTFAVET

21. Description of experiment and used technical apparatus

That experiment was defined in order to prealably test the feasibility of various methods for using future HCMM data.

It was performed on the experiment field situated near the "Station de Bioclimatologie" whose dimensions are about 70 m x 200 m.

The field is planted with grass kept short (about 5 cm) like required for measurement of potential evaporation.

It was divided into two equal parts, the north parcel being irrigated while the south was kept dry (Fig. 1).

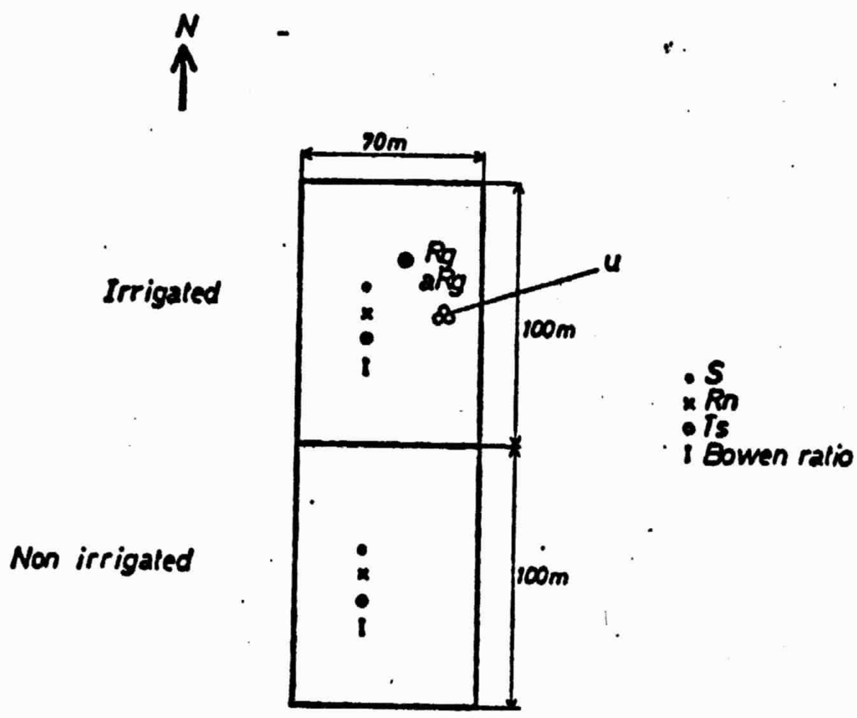

Fig. 1. Sketch of experiment field for 1977 summer

On the north part, global (Rg), reflected (aRg) and atmospheric long-wave radiation (Ra) are standarly measured together with wind velocity (u) at 2 m high.

At the center of each parcel were set up the following measurements

- net radiation Rn (differential pyrradiometer CEA-INRA)
- soil heat flux S (heat plate Thornthwaite and Co)
- Bowen ratio β (dry and wet bulb thermometers at 0.30 and 2.00 m)
- surface temperature T_s (infrared thermometer - Heimann KT 24).

These measurements were continuously recorded with a 1 min scanning interval on a data system integrating hourly mean values from 15 July to 20 September. At the present time, only the 15 July-31 August period has been analyzed, so that presented results will be limited to it.

22. Results of measured evaporation by Bowen ratio method

Before discussing results concerning infrared thermometry, it seems useful to first indicate that 1977 summer was somewhat rainy, in contrast to usual mediterranean climate weather. So that the expected contrast between "dry" and "wet" halves of the experiment field was very limited and in fact inexistent (except may be for september which has not been analyzed at the present time).

That could be verified on fig. 2, where are reported, together with registered rainfall, daily values of the ET_β/Ep ratio corresponding to Effective ET/Potential ET index.

ET_β corresponds to daily values of evaporation as measured by the Bowen ratio method on a hourly basis.

Ep corresponds to daily values of potential evaporation as calculated by Penman formula for a grass surface (with the wind function $f(u) = 0.26(1.0+0.54u)$ also on a hourly basis. (It could be added to that figure that the last rainfall before reported 20 July occured on June 19 with 17 mm and June 28 with 14 mm).

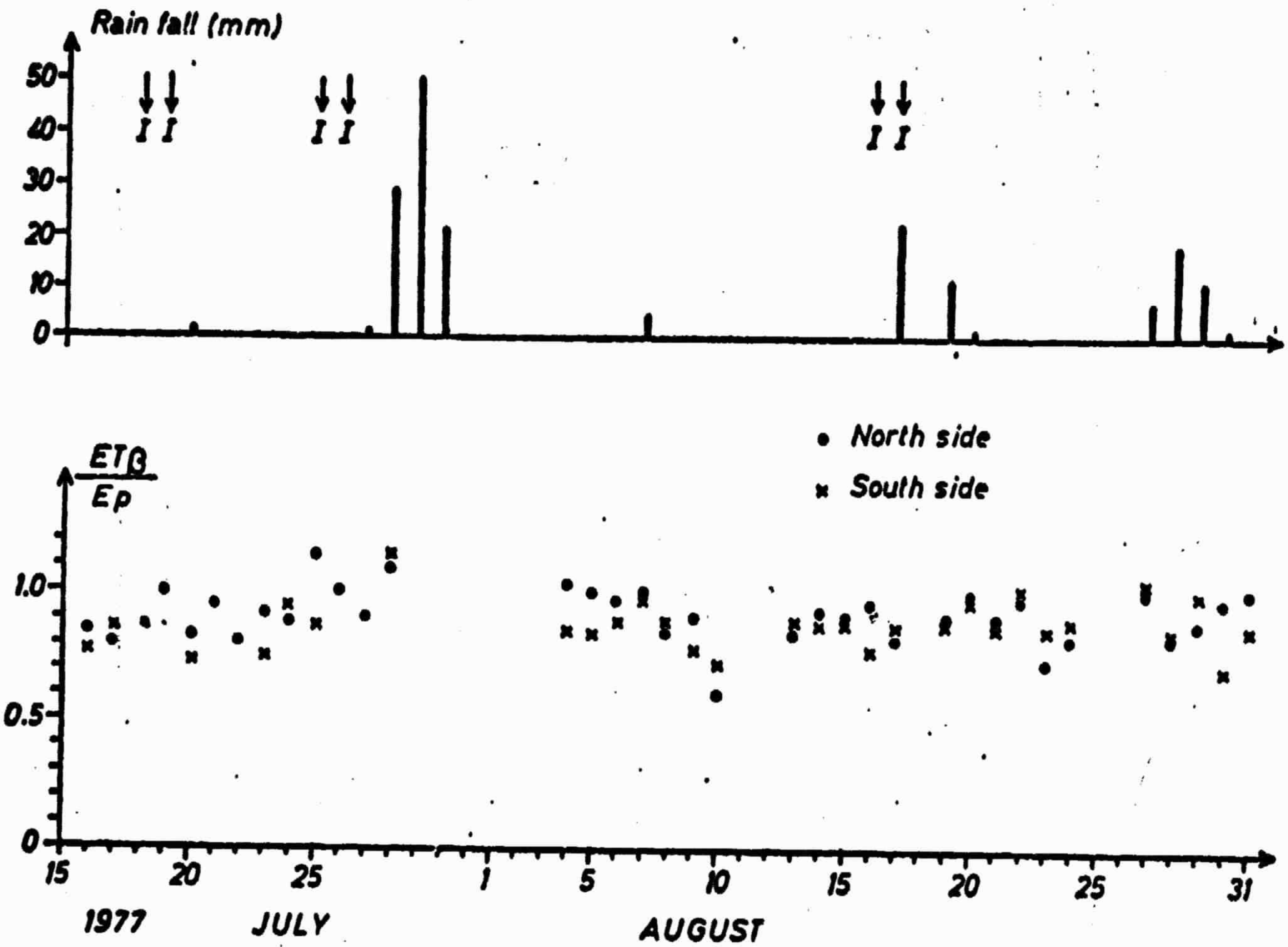

Fig. 2. Variation of daily ET_β/Ep values during 15 July-31 August period together with measured rainfall for the same period

It then appears that ET_β/Ep ratio was grossly maintained between 0.8 and 1.1 for the two parcels, so that no clear available water restriction occured, even for the "dry" parcel.

The only clear difference was encountered for net radiation measurements, since daytime Rn was systematically lower on the south side by about 10 to 15 %, leading to a similar reduction for calculated Ep values. That could be attributed to a systematic error in Rn measurement, but previous experiments with the two differential pyrradiometers close together during 3 days displayed only 2 % to 3 % deviation. It then seems that the observed reduction may be considered as significant. Since measured surface temperatures were not significantly different, the explanation lies in an increase of albedo for the south side. It is sure that grass was visually whiter on south, which may be attributed to drier conditions during winter and spring. Computations of albedo, using measured Rn and Ts on south side together with Rg and Ra on the north reference field, gave typical values of the order of 0.25 - 0.27 compared to standard values of 0.19-0.20 for the north side. So that the increase of albedo with drying conditions for grass appears as a significant term accounting for about 10 % (or more for drier conditions) in net radiation.

23. Thermal inertia approach

The thermal inertia approach, for which HCMM has been originally planned, has been analyzed by considering differential values of Ts between hourly mean values for 0-1 hr TU and 12-13 hr TU periods (which grossly corresponds to 1.30 hr a.m and p.m in solar time).

It may be observed that, in spite of the limited range of variation of water availability conditions (and then of soil moisture content), the day-night tempereature difference exhibits large variations. As it could be expected from energy budget considerations, these variations are linked, to the first oder, to variations of solar (or net) radiation, as shown by the fig. 3. The wind velocity appears as a second order parameter being able to widely reduce ΔT in some circumstances (15-21-22 July - 10-27 August).

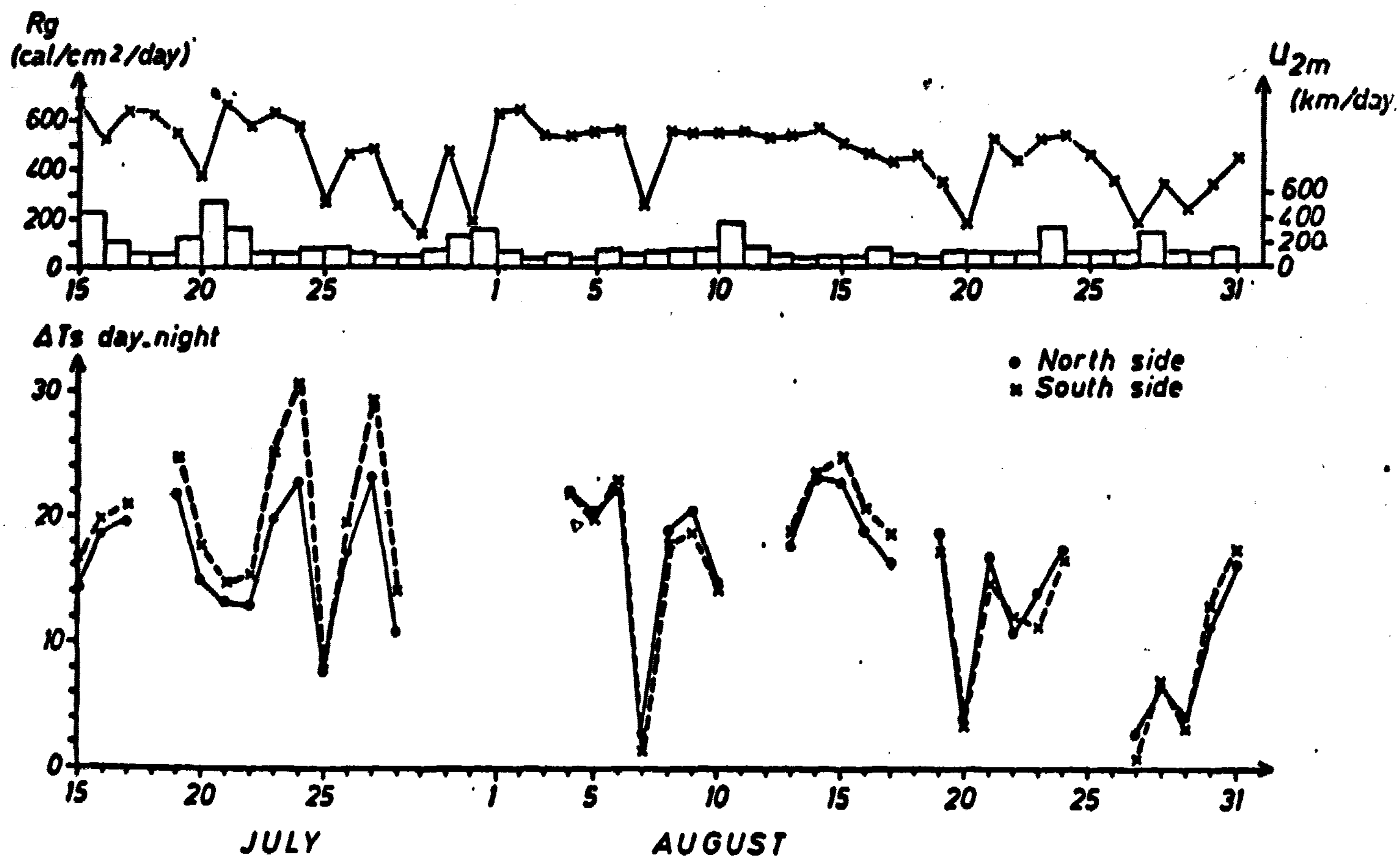

Fig. 3. Evolution of the day-night temperature difference ΔT_s together with global radiation and wind velocity

The strong influence of radiation upon ΔT_s may be displayed by considering the relation between the two parameters (Fig. 4).

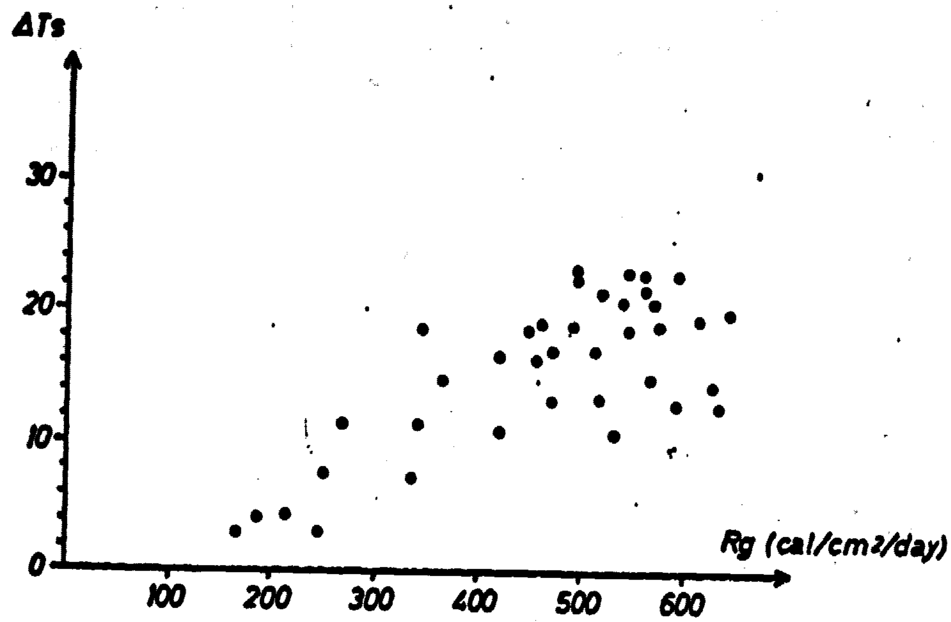

Fig. 4. Relationship between ΔT_s and global radiation for the north side

It then appears that, in spite of the well known effect of soil moisture on ΔT_s, solar radiation and wind velocity will so much damp it, especially for only every 8 days data, that ΔT_s can hardly be used to detect water availability, in opposition to the findings of REGINATO and al (1976) for bare soil. That statement would be less firm for continuous daily data, since a long-term trend might be expected to appear in relation to soil moisture evolution, but we consider it as well established for weekly spaced data.

24. Differential thermography approach

Due to the expected 1 to 2° at least incertitude about absolute temperature values which will be given by the satellite (problems of atmospheric corrections), we indicated during previous meetings that we should try to use a differential approach. It is based on the relationship between water vapour flux difference and corresponding surface temperature difference between similar surfaces only differing by water regime.

If soil heat fluxes and albedo change are neglected, the simple comparison of energy budgets for the two surfaces leads to the following equations

$$(1-a)\ Rg + R_A - \sigma T_{s1}^4 = ET_1 + \rho Cph\ (T_{s1}-T_a)$$

$$(1-a)\ R_g + R_A - \sigma T_{s2}^4 = ET_2 + \rho Cph\ (T_{s2}-T_a)$$

So that it could be written, as stated by ITIER and PERRIER (1974)

$$ET_1 - ET_2 = (4\ \sigma T^3 + \rho\ C_{ph})\ (T_{s1} - T_{s2})$$

If the evaporation of a reference surface (for instance, but not necessary, potential evaporation for a large irrigated surface) is known, deviations of effective evaporation ΔET could be calculated by a simple linear relationship with corresponding ΔT_s.

It was planned to test that approach during 1977 experiment by the comparison between "dry" and "wet" parcels, but that study could not be achieved as explained above.

So that we will be obliged to test it directly during HCMM experiment, keeping in mind that the hypothesis of negligible influence of albedo change may lead to 10 % or more error upon net radiation and then evaporation rates.

25. Combined aerodynamic energy-balance approach

That approach, used by BROWN and ROSENBERG (1972) and STONE and HORTON (1974) simply consists in calculating the sensible heat flux H by the aerodynamic equation relating flux to temperature difference $T_s - T_a$, then deriving the latent heat flux ET from the energy budget.

$$H = \rho\ Cp\ h\ (T_s-T_a) \quad \text{or} \quad H = \rho\ Cp\ \frac{(T_s-T_a)}{r_a}$$

$$ET = R_n - S - H$$

(The last equation corresponds to the general case, but signs may be changed for advective conditions or for short periods when net radiation is changing of sign on morning and evening).

The two critical points for that method are

1) as T_s and T_a are measured by different physical processes, systematic errors of about 1 to 2° may be encountered for the difference T_s-T_a

2) the determination of heat exchange coefficient h is not an easy one, due to the determination of roughness parameter z_o and to stability corrections.

So that we considered it with some scepticism. In fact, 1977 experiment was encouraging for that approach using infrared thermometers for determining T_s (the use of satellite values may be less satisfactory for that point).

h was determined using u_{2m}, assuming a standard value of 0.5 cm for z_o and taking the same stability corrections as adopted by SOER (1977) by the following procedure :

h is first calculated by assuming neutrality, so that

$$h_N = \frac{k^2 u}{(\log \frac{z}{z_o})^2}$$

A "neutral" value for H is then derived $H_N = \rho C_p\, h_N (T_s - T_a)$ from which is calculated a first-order Monin-Obukhov length $L = \frac{\rho C_p\, T u_*^3}{k g\, H_N}$

h is then recalculated by using stability corrections as follows

- if $T_s > T_a$ $\quad h = \frac{k^2 u}{(\log\frac{z}{z_o} - P_1)(\log\frac{z}{z_o} - P_2)}$

with $P_1 = 2 \log (\frac{1+x}{2}) + \log (\frac{1+x^2}{2}) - 2 \text{ Arc tg } x + \frac{\pi}{2}$

$P_2 = 2 \log (\frac{1+x^2}{2})$

$x = (1 - 16 \frac{z}{L})^{0.25}$

- if $T_s < T_a$ $\quad h = \frac{k^2 u}{[\log\frac{z}{z_o} + 4.7 \frac{z}{L}]}$

The iterative procedure is pursued until difference between two successive H values goes lower than 2 %.

We said that results were encouraging since the agreement between Bowen ratio method (which may be considered as the standard reference) and ET values by that approach was good, as well for hourly values as for daily values. It has to be noted, however, that use of the T_s method generally gives midday values of ET significantly smaller than Bowen ratio method by about 20 %, then corresponding to an equivalent overestimation of H. That could be due to a systematic error in T_s measurement (too high) or in the determination of r_a (too low).

That may be verified from the listed values reported in the annex tables II and III and considering fig. 5 for a typical day and fig. 6 - 7 summing up 12-13 hr and daily values.

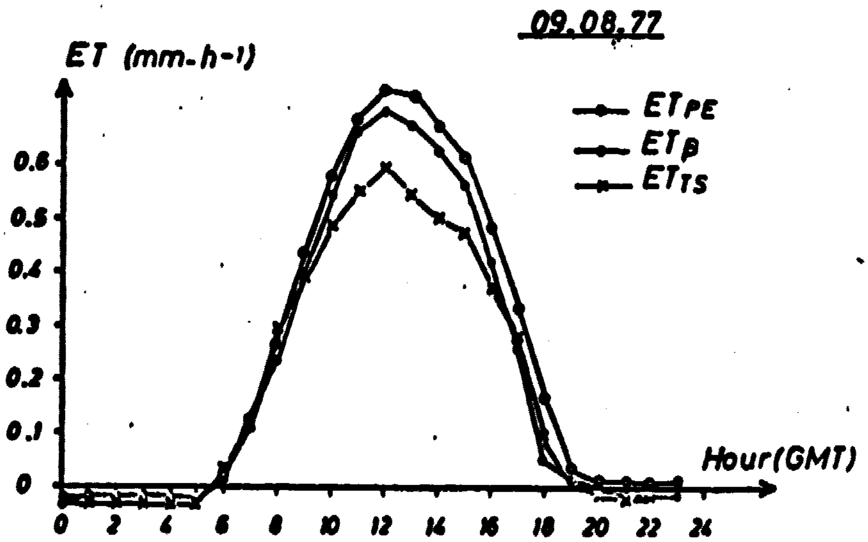

Fig. 5. Hourly values of potential evaporation (Penman formula) and effective evaporation by Bowen ratio and T_g methods for a typical clearday (9/8/77)

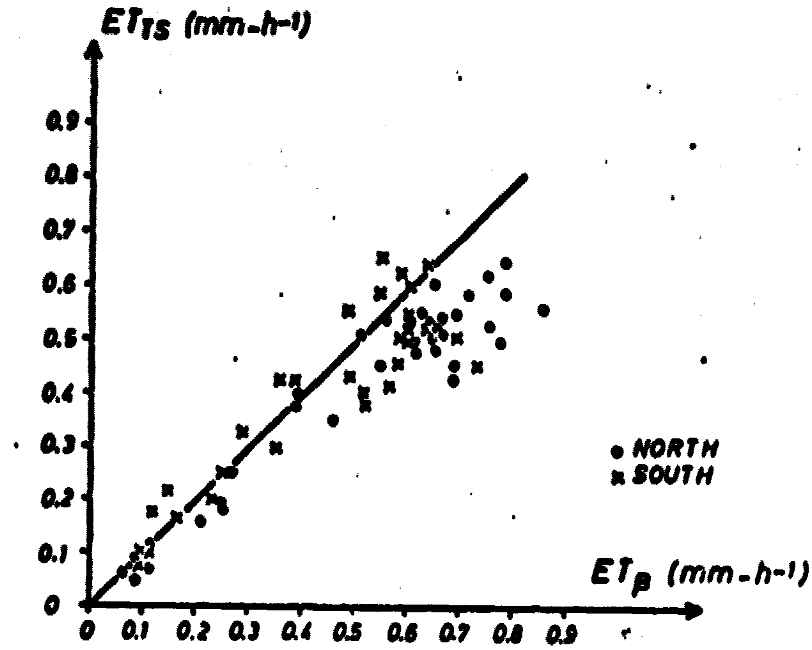

Fig. 6. Relation between hourly values (12-13 hr TU time) of ET_β and ET_{Ts} during 1977 summer experiment

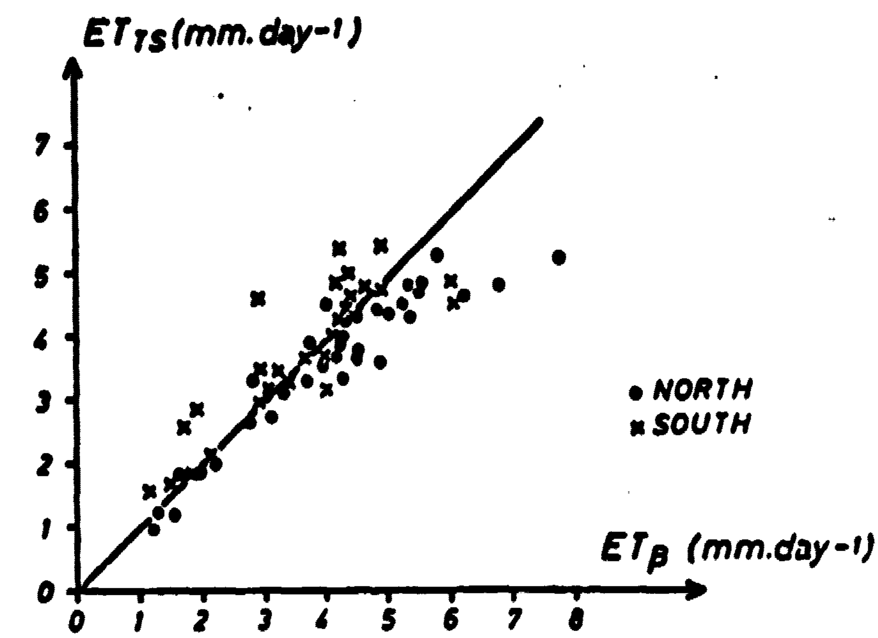

Fig. 7. Relation between integrated daily values of ET_β and ET_{Ts} during 1977 summer experiment

2.6. Application to the indirect determination of surface humidity

When potential evapotranspiration as defined by PENMAN occurs, the surface is supposed to be saturated so that the surface water vapour pressure e_s corresponds to :

$$e_s = E\,(T_s)$$

This is hardly encountered in nature, even for well-watered cultures (PERRIER 1975) and, by all ways, when water is restricted, so that appear a surface saturation deficit $E\,(T_s) - e_s$ and a surface relative humidity Hr_s smaller than 1.

One or the other of these parameters, which are linked by the relation

$$E(T_s) - e_s = E(T_s)\,[1 - Hr_s],$$

is essential for fixing the rate of actual ET, as shown by TANNER and FUCHS (1968) for the extension of the Penman combination concept for non saturated surfaces and by VAN BAVEL and HILLEL (1976) and KOSLMA (1977) in simulating evaporation from bare soil.

Due to the quasi impossibility to measure it directly in the present stage of experimental methods, surface humidity Hr_s is generally unknown and very few experimental data has been presented considering it.

It is however possible to derive it indirectly from the last paragraph results, since ET can be written

$$ET = \rho\, C_p\, h\, \frac{e_s - e_a}{\gamma} \qquad \text{or} \qquad ET = \rho\, Cp\, \frac{1}{\gamma}\, \frac{e_s - e_a}{r_a}$$

So that e_s may be estimated from the measurement of e_a and the derivation of ET by the exposed method, and Hr_s calculated as $\frac{e_s}{E(T_s)}$.

Obtained values of H_{rs} and $E(T_s) - e_s$ are presented and compared to the corresponding air values on the following figures 8-9 for hourly data on a typical day and 10-11 for midday values (12.00-13.00 hr) during the whole experiment campaign.

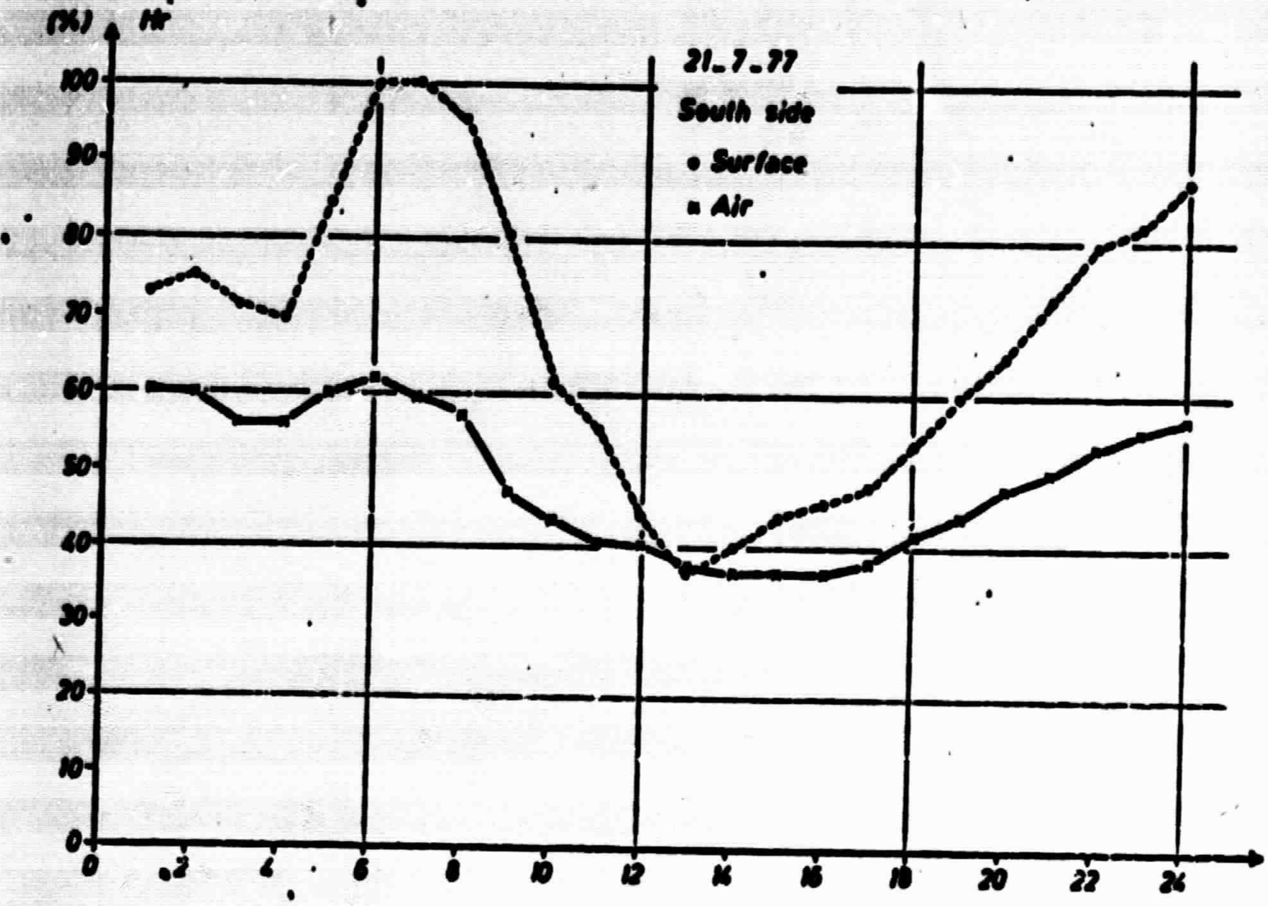

Fig. 8. Hourly values of derived Hr_s and measured Hr_a (at 2 m high) for a typical clear day

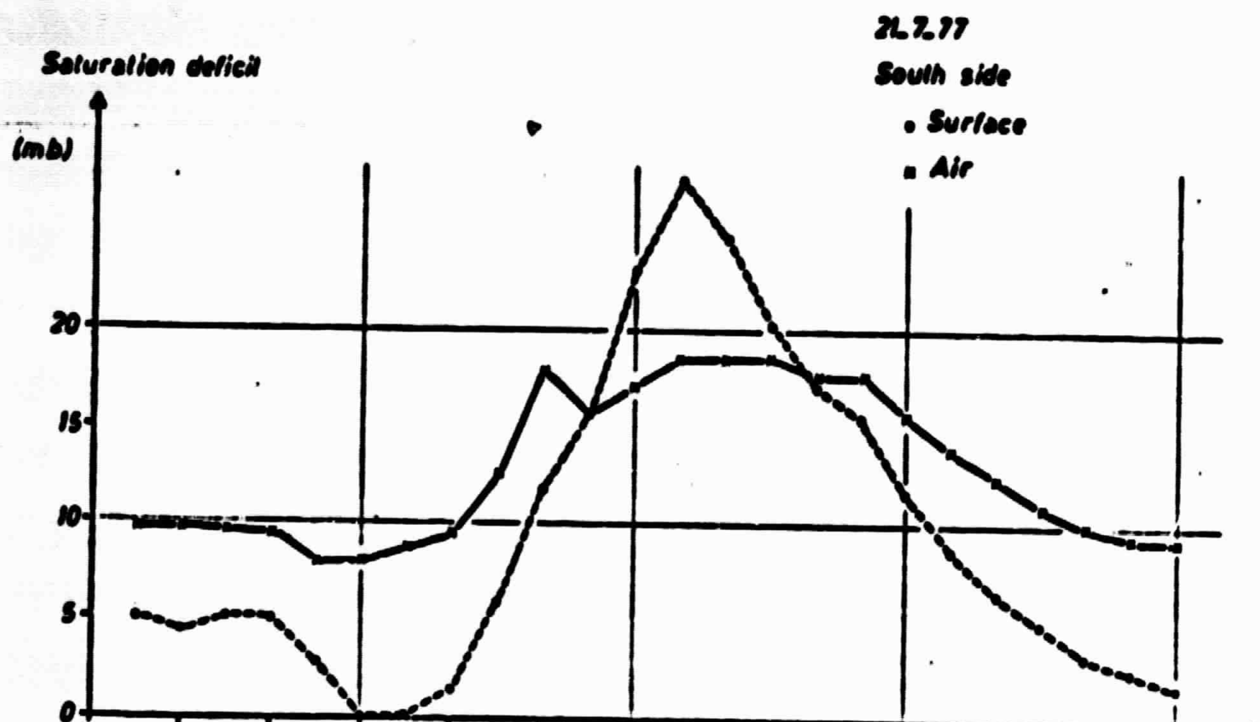

Fig. 9. Hourly values of derived $E(T_s)-e_s$ and measured $E(T_a)-e_a$ (at 2 m high) for a typical clear day

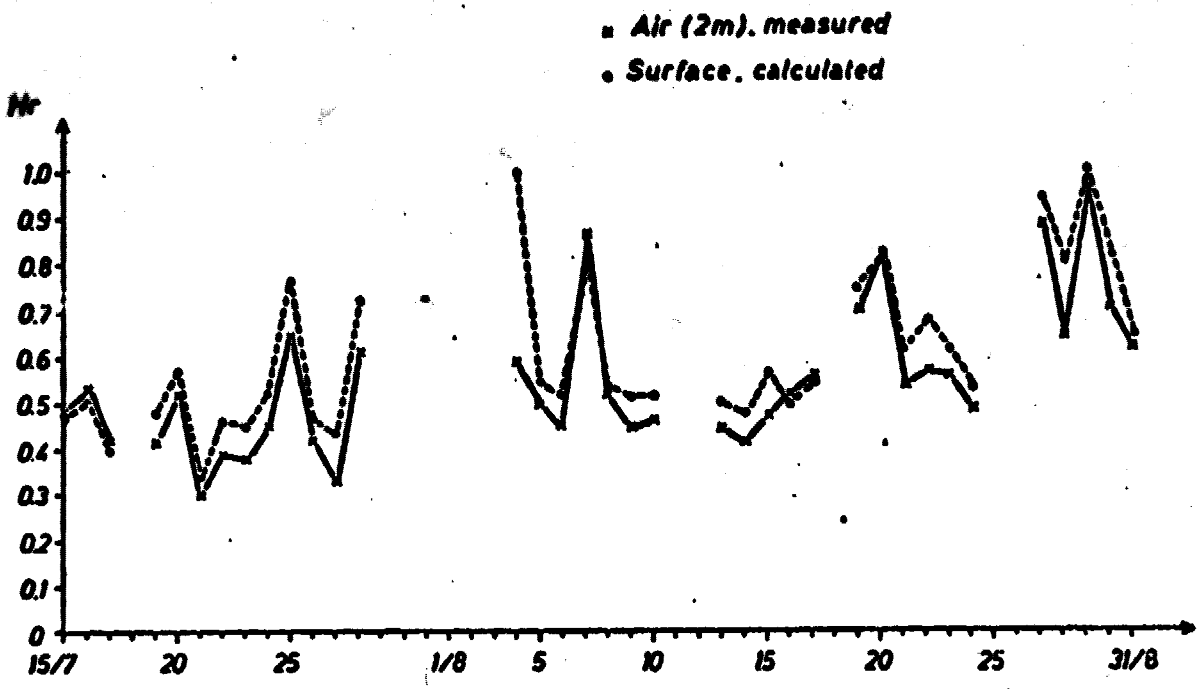

Fig. 10. Evolution of midday values (12.00 - 13.00 hr) of derived Hr_s and measured Hr_a (2 m high)

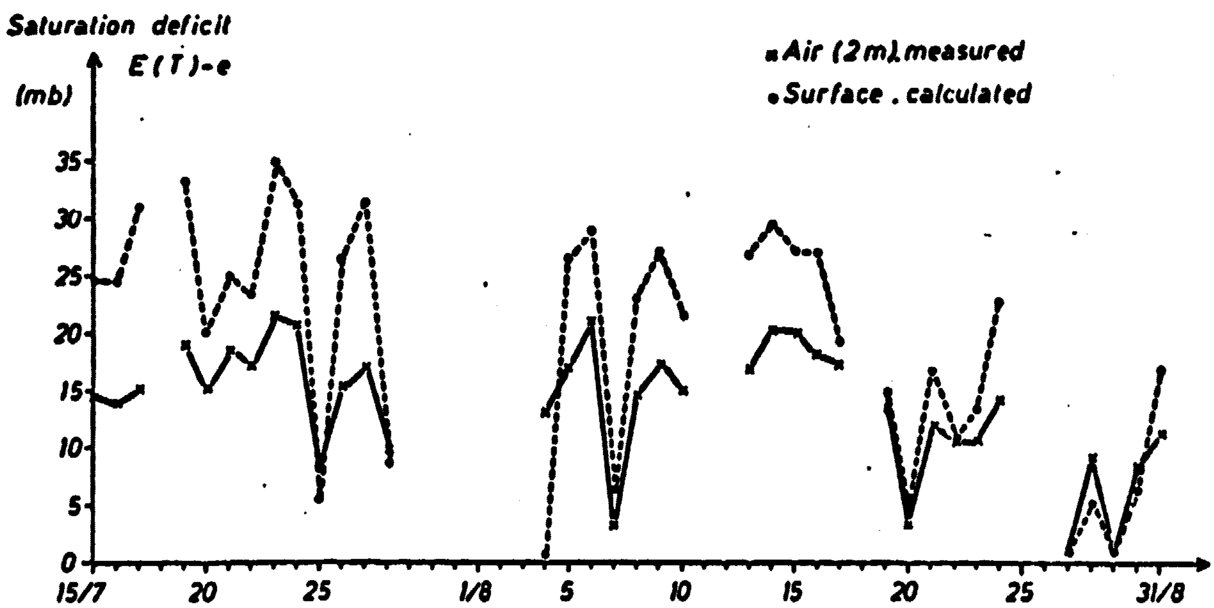

Fig. 11. Evolution of midday values (12.00 - 13.00 hr) of derived $E(T_s)-e_s$ and measured $E(T_a)-e_a$ (2 m high)

The following comments may be formulated concerning surface relative humidity and surface saturation deficit

: for the diurnal course (fig. 8-9), Hr_s tends to follow the course of Hr_a with a more contrasted evolution between night values (practically always 1.00 indicating saturation) and midday values close to Hr_a (higher and sometimes close to 1.00 in "humid" periods - slightly smaller on "dry" periods) (fig. 10). Due to the general excess of T_s compared to T_a, $E(T_s) - e_s$ is generally higher than $E(T_a) - e_a$ (fig. 9 and 11), except after rain or irrigation (fig. 12).

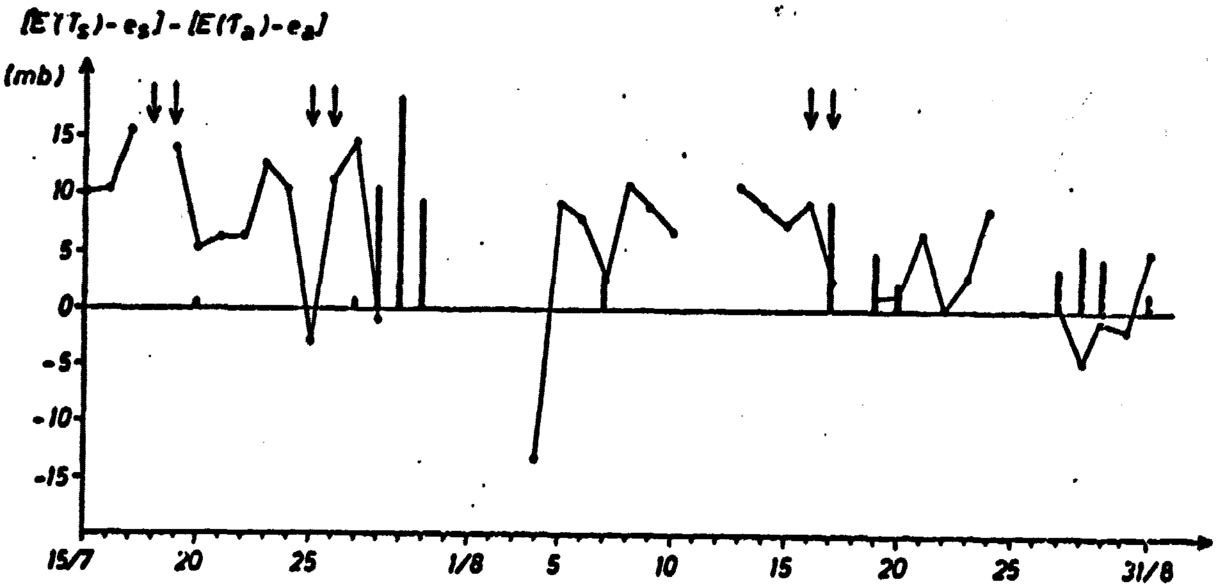

Fig. 12. Evolution of the difference $[E(T_s)-e_s] - [E(T_a)-e_a]$ for midday values (12.00 - 13.00 hr) together with rain and irrigation data

The validity of Hr_s and $E(T_s)-e_s$ derived values is evidently depending upon the validity of the estimation of ET by the method exposed in 2.5. As we have noted some persistent underestimation of midday values of ET compared to the reference Bowen ratio method, it could be thought that Hr_s is slightly underestimated and $E(T_s)-e_s$ conversely slightly overestimated, but given values may be considered with some confidence (say within a limit of 10 %) as indicative for these parameters for which few experiment data are available.

By the same way, it would also be possible to derive indirect values for the stomatal resistance r_s of the considered grass canopy, since ET may also be written as

$$ET = Cp \frac{1}{\gamma} \frac{E(T_s)-e_a}{r_a + r_s}$$

then giving the following relationship

$$\frac{r_s}{r_a} = \frac{E(T_s) - e_s}{e_s - e_a}$$

When applied to days for which ET estimation by using T_s method closely follows the reference Bowen ratio ET value (for instance 10.8 - 19.8 - 23.8), in order to avoid errors due to the inadquacy of T_s method, r_s values so obtained for midday conditions range from about 40 $s.m^{-1}$ after rain to about 70-100 $s.m^{-1}$ in "dryer" stages. These values are just given as tentative in order to illustrate the possibilities of that method which has to be correctly tested.

2.7. Test of the simplified JACKSON et al (1977) procedure

Two major points arise when the systematic use of paragraph 2.5. procedure is to be used.

- the significance of T_s when applied to tall canopies
- the tedious procedure needed to estimate the exchange coefficient h or the atmospheric resistance r_a.

The first appeals specific studies for coming years, while the second would justify the use of a simplified procedure if possible to establish a precise enough one.

That is the purpose of the method proposed by JACKSON et al (1977) in their study concerning wheat and the feasibility of determining its water requirements from canopy temperature.

Starting from the observation that, in their conditions, it was not possible to detect a specific dependance of h against u, they try to convert the wind factor (otherwise h or r_a) into a constant. Moreover, they propose to pass directly to daily values of ET by using only daily Rn ande one-time-of-day measurement of $T_c - T_a$ by the following simple relationship

$$ET = R_n - B\,(T_s - T_a)$$

That is an interesting procedure, since

1) the complex calculation of r_a is avoided
2) results for ET are gained directly on a daily basis, which is the interesting scale time for water use studies.

Its character of simplicity is really appealing, but it is necessary to verify its applicability to conditions other than those for which it was established (i.e. wheat in the climate of Arizona).

In fact, four questions can be asked about it when applied to our data (i.e short grass in the climate of Avignon)

a) is h really independent of u ?
b) is it justified to use the energy balance on a daily time scale combined with a one-time-of-day estimation of the sensible heat flux H ?
c) is it possible to derive a B constant in the same manner as JACKSON and al ?
d) and, if so, is it close to the numerical value they obtained or very different from it ?

The answer to the first question a) appears in fig. 13, where f(u) derived from ET values measured by Bowen-ratio method is plotted against u for 12-13.00 hr period of each day. In spite of a large scattering, it seems to appear a marked tendency for f(u) to increase with u when it exceeds 2 $m.sec^{-1}$. Even if the expression derived from logarithmic profiles $f(u) = 4.4 \times 10^{-3}\, u$ and moreover corrected values for stability effects do not give a quite good approximation of exact f(u) (they tend to overestimate it, especially with corrections of unstability, which explain the corresponding underestimation of ET by the T_s method), it seems hardly possible to take f(u) as a constant, at least in our conditions.

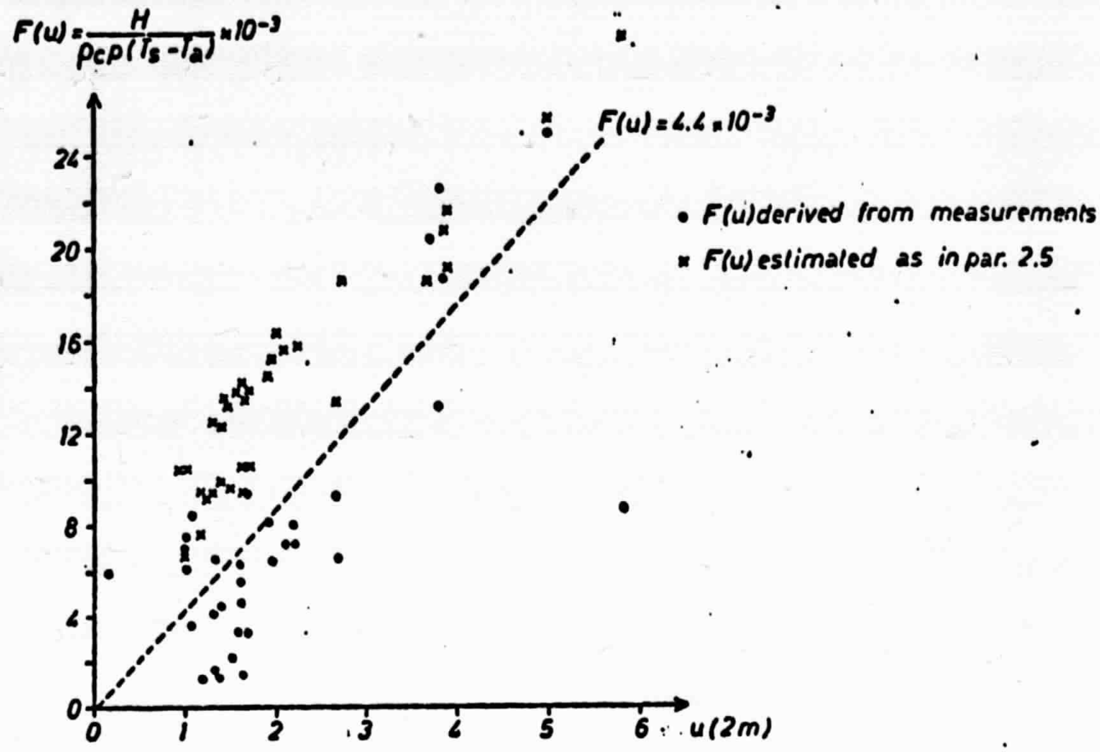

Fig. 13. Values of f(u) derived from hourly measured values of energy budget and $T_s - T_a$ (12.00-13.00 hr) plotted agains u (.), together with estimated values as calculated in par. 2.5 (x)

The answer to questions b) c) d) arise from fig. 14, where daily values of ET - R_n and ET alone are plotted agains $T_s - T_a$ for the 12.00-13.00 hr period, which is exactly the same presentation as in JACKSON et al. paper.

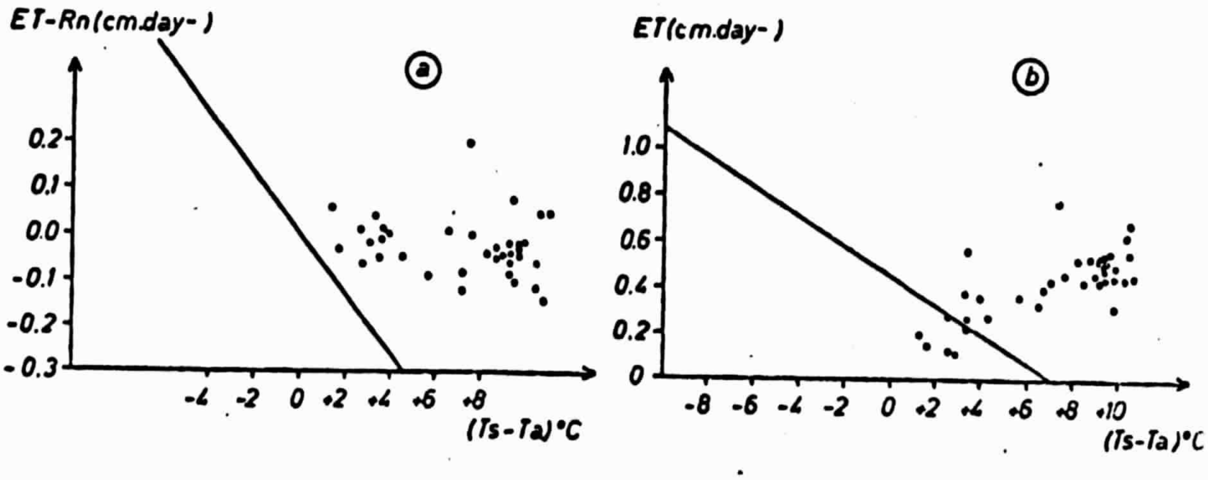

Fig. 14. Daily ET-R_n and ET as a function of T_s-T_a. The marked line corresponds to the data of JACKSON et al (1977)

It first appears (question b) that the mixing of time scales between daily values for ET and R_n and hourly values for T_s - T_a does not create serious problems since the observed scattering is not too large. That seems to indicate that climatic conditions are stable enough during the diurnal cycle for summer conditions in Avignon as in Phoenix to ensure midday conditions being representative of the whole day.

The reduced scattering already noted also implies a positive answer to the third question c) : yes, it is possible to derive a constant B, which is different for ET - R_n or ET alone (of the order of 0.005 and - 0.05 respectively, with the same units as in JACKSON et al. study).

But these values (answer to question d) are completely different from the 0.064 value given by JACKSON et al., which is not really surprising as noted by them in stating that "evaluation of B for other locations would require local calibration".

That seems to be due both to the local climate and the crop considered.

The fact that the slope in fig. 14a is by far smaller than in JACKSON et al. work is quite logical since grass is smoother than wheat (especially for small plots of the Phoenix test presumably leading to some local advection systems).

The opposition in climate between Phoenix and Avignon (especially for that wet summer in the second place) is also clearly established in the two figures where the range of variation of T_s - T_a extends only between 0 and + 8° while it occurs between - 6 and + 2° in Phoenix. Thus, advective conditions (ET > R_n) are predominant in the case of Phoenix and not in Avignon, which could also explained by the small dimensions of wheat plots in Phoenix experiment.

That opposition between the two local climates is also responsible of the complete difference of the relationship form between ET and T_s - T_a (fig. 14 b) for the two places. The slope is negative in Phoenix, which could be interpreted as resulting from a fairly constant climatic system (for both Rn and regional advective conditions). So that the main source of variation arises from water availability from wheat, leading to smaller values of ET when T_s is high.

On the contrary, in Avignon, water supply was not severely restricted, so that in fact high values of T_s - T_a tend to indicate clear summer days with high radiation and then high evaporation.

As it was possible to predict, the use of JACKSON et al approach, while feasible for a given location and culture, is highly dependent upon the kind of culture, the field dimensions (because of its advective implications) and the local climate not only in space but also in time. It may be thought that results would have been very different in Avignon with a usual dry summer leading to more pronounced advective conditions (PET for may-august period amounted to 560 mm only compared to a 10 year mean value of 670 mm).

So that it seems hardly possible to use it in the frame of Tellus project with only sparse measurements of T_s - T_a, which is in fact the same statement as for day-night temperature differences related to thermal inertia (par. 23).

III. FINAL ARRANGEMENT FOR TELLUS PROJECT

31. Location of field experiments

As justified above, 1978 experiment will be concentrated on the Crau plain by considering irrigated pastures and natural dryland grass surfaces. These are widely represented in Crau, as shown by Fig. 15.

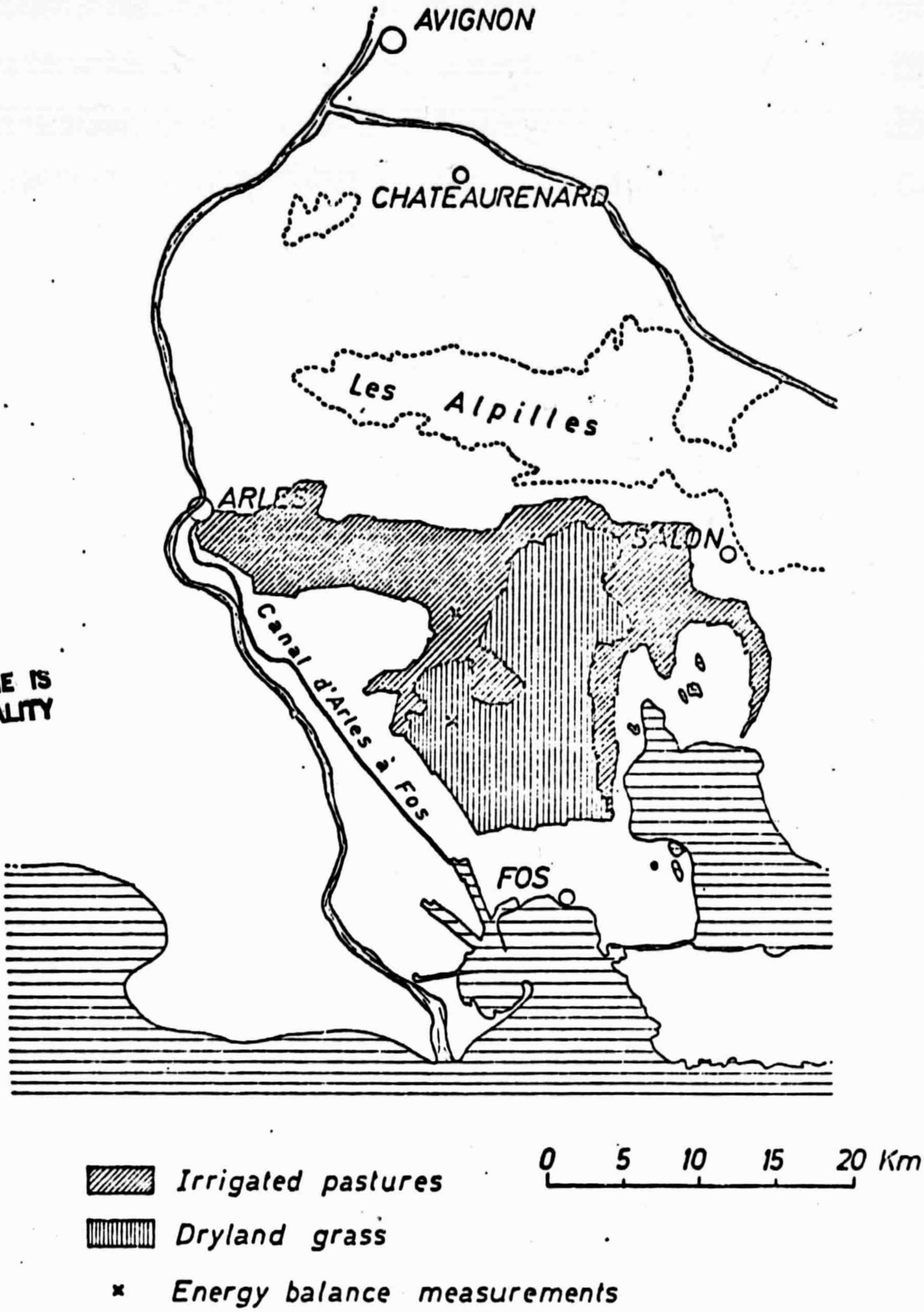

Fig. 15. Map of the "Crau" plain with indication of irrigated pastures and natural dry grass

Two sites have been selected

- one in a large pasture irrigated area (about 200 ha)
- the other in a dry lucerne culture (about 30 ha) surrounded by large dry surfaces (100 km^2).

32. Planned measurements

In each site, will be taken the following measurements

- Rg
- Rn
- S
- u at 2 m
- Bowen ratio at 0.30 and 2.00 m (dry and wet-bulb temp.)
- soil tem. at 0.10 m and 0.50 m depth.

In addition, soil moisture will be followed (if possible) by neutron probes in the dry site.

These data will be registered on "Schlumberger" automatic recording systems and treated in Montfavet. That apparatus will be available by a financial grant from French DGRST, by the way of a research contract on the general theme of "Water management in mediterranean region". For that contract, our laboratory is associated to "Ecole des Mines - Laboratoire d'Hydrogéologie Mathématique de Fontainebleau" and "Ecole des Mines - Laboratoire de Télédétection et d'Analyse des Milieux Naturels de Valbonne". These laboratories will develop a parellel research, either by hydrologic model studies or by remote sensing data analysis (especially treatment of daily data received by NOAA satellites, which could complete HCMM informations).

33. Data treatment

From HCMM data when available will be calculated spatial variations of ET instantaneous values both by differential thermography and combined aerodynamic energy balance approaches by the following manner

- since ET_{dry} and ET_{wet} are measured, the coefficient α as defined by $\Delta ET = \alpha (\Delta T_s)$ will be determined and compared to $(4\sigma T^3 + \rho Cp\ h)$. Intermediate values between the two sites will be linearly extrapolated
- T_s values will be used to calculate ET_{Ts}, by assuming a constant z_o, u and T_a value for the whole land. Rn will be modulated using albedo and T_s values derived from HCMM data as follows

$$R_{ni} = (1-a_i)\ Rg + Ra - \sigma T_{si}^{\ 4}$$

assuming a constant regional value for Rg and Ra.

Obtained ET_{Ts} values will be tested in dry and wet fields by comparison to ET .

34. Use of obtained data

These treatment will give a small-scale mapping of instanteneous 1.30 p.m values of ET for Crau plain (at least short grass surfaces).

These instanteneous values will be converted to daily values by following the diurnal course of measured ET in dry and wet reference zones or calculated Ep.

Daily values will be extended to longer term (8 days or 16 days depending upon HCMM data availability) periods

- by the same extrapolation process as for the diurnal course
- by using NOAA data when available
- by using simple water balance model adjusted to the daily obtained values of ET.

So that it is expected to get continuous recording of small-scale ET and regional ET, from which some specific values may be verified by comparison with precise hydrological small scale basin studies.

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Annex I

DAILY VALUES OF DAY-NIGHT SURFACE TEM. DIFFERENCES

DATE	NORTH			SOUTH		
	$T_{s(0-1)}$	$T_{s(12-13)}$	ΔT_s day-night	$T_{s(0-1)}$	$T_{s(12-13)}$	ΔT_s day-night
15/7	17.1	31.5	14.4	15.0	31.2	16.2
16	14.3	32.8	18.5	12.4	32.2	19.8
17	13.8	33.6	19.8	12.4	33.2	20.8
19	14.4	36.2	21.8	12.7	37.9	25.2
20	16.3	31.4	15.2	14.8	32.0	17.8
21	17.3	30.7	13.4	15.8	30.3	14.5
22	14.5	27.4	12.9	12.2	27.9	15.7
23	16.3	37.0	19.7	14.3	39.3	25.0
24	14.2	37.5	23.3	12.8	43.2	30.4
25	14.1	22.0	7.9	13.4	21.5	8.1
26	13.8	31.2	17.4	12.0	31.3	19.7
27	9.9	33.5	23.6	7.7	37.0	29.3
28	13.9	24.8	10.9	11.5	25.5	14.0
4/8	13.5	34.2	21.7	13.6	35.4	21.8
5	15.2	35.5	20.3	15.2	35.1	19.9
6	14.9	36.9	22.0	15.2	37.2	22.0
7	18.2	21.4	3.2	18.0	18.7	0.7
8	14.7	33.6	18.9	12.5	30.3	17.8
9	14.4	34.6	20.2	13.8	33.1	19.3
10	16.4	31.1	14.7	14.9	29.3	14.4
13	14.8	33.6	18.8	13.4	32.3	18.9
14	12.7	35.6	22.9	12.1	35.2	23.1
15	14.6	37.2	22.6	14.0	38.8	24.8
16	16.3	35.3	19.0	16.2	36.7	20.5

20	16.3	31.4	15.2	14.8	32.0	17.8
21	17.3	30.7	13.4	15.8	30.3	14.5
22	14.5	27.4	12.9	12.2	27.9	15.7
23	16.3	37.0	19.7	14.3	39.3	25.0
24	14.2	37.5	23.3	12.8	43.2	30.4
25	14.1	22.0	7.9	13.4	21.5	8.1
26	13.8	31.2	17.4	12.0	31.3	19.7
27	9.9	33.5	23.6	7.7	37.0	29.3
28	13.9	24.8	10.9	11.5	25.5	14.0
4/8	13.5	34.2	21.7	13.6	35.4	21.8
5	15.2	35.5	20.3	15.2	35.1	19.9
6	14.9	36.9	22.0	15.2	37.2	22.0
7	18.2	21.4	3.2	18.0	18.7	0.7
8	14.7	33.6	18.9	12.5	30.3	17.8
9	14.4	34.6	20.2	13.8	33.1	19.3
10	16.4	31.1	14.7	14.9	29.3	14.4
13	14.8	33.6	18.8	13.4	32.3	18.9
14	12.7	35.6	22.9	12.1	35.2	23.1
15	14.6	37.2	22.6	14.0	38.8	24.8
16	16.3	35.3	19.0	16.2	36.7	20.5
17	15.0	31.1	16.1	14.6	33.2	18.6
19	13.2	31.7	18.5	12.5	30.0	17.5
20	17.8	21.8	4.0	16.2	20.0	3.8
21	13.9	30.8	16.9	12.7	27.1	14.4
22	13.6	24.6	11.0	11.1	23.3	12.2
23	12.5	26.3	13.8	10.8	22.4	11.6
24	14.2	31.9	17.7	11.5	28.2	16.7
27	14.9	17.9	3.0	13.7	14.1	0.4
28	15.2	22.4	7.2	12.9	20.1	7.2
29	14.8	18.9	4.1	10.9	15.8	3.9
30	14.2	25.9	11.7	11.7	24.9	13.2
31	15.7	31.9	16.2	16.2	32.0	17.3

Annex II

EVAPORATION VALUES FOR 12-13 hr TIME (in $mm.hr^{-1}$)

DATE	NORTH SIDE			SOUTH SIDE		
	Ep	ET_{β}	ET_{Ts}	Ep	ET_{β}	ET_{Ts}
15/7	0.79	0.66	0.52	0.72	0.57	0.44
16	0.68	0.62	0.48	0.61	0.39	0.41
17	0.76	0.68	0.45	0.70	0.52	0.38
19	0.81	0.85	0.56	0.68	-	0.37
20	0.47	0.46	0.35	0.44	0.35	0.30
21	0.97	0.78	0.50	0.86	-	0.43
22	0.58	0.38	0.40	0.52	0.29	0.33
23	0.82	0.78	0.59	0.79	0.69	0.50
24	0.81	0.79	0.64	0.81	0.73	0.45
25	0.12	0.08	0.09	0.10	0.10	0.10
26	0.66	0.69	0.43	0.64	0.51	0.41
27	0.71	0.75	0.53	0.68	-	0.38
28	0.25	0.25	0.20	0.24	0.11	0.17
4/8	0.57	0.58	-	0.55	0.49	-
5	0.71	0.67	0.54	0.67	0.60	0.51
6	0.74	0.72	0.58	0.70	0.62	0.53
7	0.09	0.09	0.05	0.09	0.10	0.10
8	0.74	0.69	0.55	0.71	0.63	0.64
9	0.72	0.67	0.53	0.69	0.60	0.55
10	0.77	0.57	0.54	0.73	0.54	0.59
13	0.70	0.62	0.50	0.66	0.58	0.51
14	0.72	0.65	0.53	0.68	0.60	0.51
15	0.68	0.63	0.55	0.66	0.60	0.50
16	0.69	0.65	0.48	0.67	0.56	0.41
17	0.26	0.21	0.16	0.25	0.16	0.11
19	0.65	0.65	0.60	0.62	0.61	0.60
20	0.10	0.11	0.07	0.10	0.10	0.10

23	0.82	0.78	0.59	0.79	0.69	0.50
24	0.81	0.79	0.64	0.81	0.73	0.45
25	0.12	0.08	0.09	0.10	0.10	0.10
26	0.66	0.69	0.43	0.64	0.51	0.41
27	0.71	0.75	0.53	0.68	-	0.38
28	0.25	0.25	0.20	0.24	0.11	0.17
4/8	0.57	0.58	-	0.55	0.49	-
5	0.71	0.67	0.54	0.67	0.60	0.51
6	0.74	0.72	0.58	0.70	0.62	0.53
7	0.09	0.09	0.05	0.09	0.10	0.10
8	0.74	0.69	0.55	0.71	0.63	0.64
9	0.72	0.67	0.53	0.69	0.60	0.55
10	0.77	0.57	0.54	0.73	0.54	0.59
13	0.70	0.62	0.50	0.66	0.58	0.51
14	0.72	0.65	0.53	0.68	0.60	0.51
15	0.68	0.63	0.55	0.66	0.60	0.50
16	0.69	0.65	0.48	0.67	0.56	0.41
17	0.26	0.21	0.16	0.25	0.16	0.11
19	0.65	0.65	0.60	0.62	0.61	0.60
20	0.10	0.11	0.07	0.10	0.10	0.10
21	0.66	0.62	0.54	0.61	0.58	0.62
22	0.25	0.25	0.19	0.23	0.24	0.20
23	0.70	0.52	0.51	0.64	0.54	0.65
24	0.68	0.64	0.50	0.61	0.48	0.56
27	0.12	0.12	0.12	0.12	0.14	0.21
28	0.42	0.38	0.38	0.39	0.35	0.43
29	0.07	0.06	0.07	0.07	0.08	0.09
30	0.28	0.28	0.25	0.25	0.25	0.24
31	0.55	0.55	0.45	0.53	0.49	0.43

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Annex III

DAILY EVAPORATION VALUES (in $mm.day^{-1}$)

DATE	NORTH SIDE				SOUTH SIDE			
	Ep	ET_{β}	ET_{Ts}	$\frac{ET_{\beta}}{Ep}$	Ep	ET_{β}	ET_{Ts}	$\frac{ET_{\beta}}{Ep}$
15/7	7.2	5.2	4.3	0.72	6.4	4.2	4.0	0.67
16	5.3	4.5	3.8	0.85	4.7	2.9	3.5	0.62
17	6.9	5.5	4.7	0.80	6.1	4.5	4.3	0.73
19	6.8	6.8	4.8	1.0	5.8	-	3.6	
20	4.0	3.3	3.1	0.82	3.7	3.1	3.0	0.83
21	8.8	7.8	5.3	0.88	8.0		5.6	
22	8.1	5.7	5.3	0.71	7.6	-	5.7	
23	7.0	6.2	4.6	0.88	6.9	6.0	4.9	0.87
24	6.2	5.5	4.9	0.88	6.3	6.0	4.5	0.95
25	2.5	2.0	1.9	0.85	2.4	2.1	2.0	0.87
26	5.4	4.9	3.6	0.91	5.2		4.1	
27	5.6	5.0	4.3	0.89	5.4	-	3.8	
28	2.2	2.2	2.0	1.00	2.1	-	2.0	
4/8	4.5	4.7	-	1.03	4.4	3.7	-	0.84
5	5.3	5.3	-	1.00	5.1	4.2	-	0.82
6	5.8	5.4	4.8	0.92	5.6	4.9	4.7	0.88
7	1.6	1.6	1.2	1.0	1.8	1.8	1.9	1.00
8	5.6	4.5	4.3	0.80	5.5	4.9	5.4	0.89
9	5.8	5.2	4.5	0.90	5.7	4.4	4.6	0.77
10	6.6	4.0	4.5	0.60	6.2	4.4	5.0	0.71
13	5.2	4.3	4.0	0.83	4.9	4.1	4.2	0.86
14	5.3	4.9	4.4	0.92	5.0	4.3	4.2	0.86
15	4.7	4.3	4.0	0.91	4.5	4.0	3.7	0.89
16	4.6	4.5	3.6	0.97	4.4	3.4	3.1	0.77
17	4.8	3.9	3.5	0.81	4.7	4.0	3.1	0.85
19	3.2	3.1	2.7	0.97	3.2	3.0	2.9	0.93
20	1.3	1.3	1.3	1.0	1.3	1.5	1.7	1.15
21	4.8	4.3	4.0	0.90	4.7	4.1	4.9	0.87
22	3.8	3.7	3.3	0.97	3.7	3.6	3.7	0.97
23	5.2	3.8	3.9	0.73	4.9	4.2	5.4	0.86
24	5.1	4.2	3.9	0.82	4.8	4.6	4.8	0.96
27	1.2	1.2	1.0	1.0	1.2	1.2	1.5	1.00
28	3.6	2.9	3.3	0.81	3.5	2.9	4.6	0.82
29	1.7	1.6	1.8	0.94	1.6	1.6	2.5	1.00
30	2.9	2.8	2.7	0.96	2.7	1.9	2.8	0.70
31	4.1	4.1	3.6	1.0	3.9	3.2	3.4	0.84

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ORIGINAL PAGE IS OF POOR QUALITY

Annex IV

RELATIVE HUMIDITY AND SATURATION DEFICIT OF AIR (2 m) AND SURFACE (o) FOR MIDDAY PERIOD (12-13 hr)

	NORTH SIDE				SOUTH SIDE			
	H_r(2 m)	H_r(o)	$E(T_a)-e_a$ (mb)	$E(T_s)-e_s$ (mb)	H_r(2 m)	H_r(o)	$E(T_a)-e_a$ (mb)	$E(T_s)-e_s$ (mb)
15/7	0.48	0.48	14.1	24.2	0.50	0.48	14.1	25.0
16	0.53	0.51	13.9	24.2	0.97	0.51	13.8	24.5
17	0.42	0.40	15.2	31.4	0.42	0.37	16.4	31.8
19	0.41	0.48	19.2	33.3	0.50	0.39	17.4	40.3
20	0.52	0.56	15.4	20.1	0.55	0.52	14.8	22.6
21	0.30	0.33	18.9	25.2	0.36	0.36	18.4	27.3
22	0.39	0.46	17.5	23.7	0.45	0.51	16.1	17.5
23	0.38	0.45	21.8	34.8	0.37	0.37	24.5	44.8
24	0.45	0.52	20.9	31.2	0.40	0.33	24.8	50.0
25	0.65	0.76	8.2	5.5	0.75	0.93	6.5	1.5
26	0.42	0.46	14.8	26.2	0.46	0.46	14.0	23.8
27	0.33	0.43	17.2	31.5	0.38	0.33	18.3	42.5
28	0.61	0.72	9.6	9.2	0.62	0.65	9.8	10.2
4/8	0.59	1.00	13.1	0	0.58	1.00	13.2	0
5	0.50	0.54	17.5	26.8	0.50	0.54	17.5	25.6
6	0.45	0.52	21.2	29.2	0.46	0.50	19.5	30.3
7	0.87	0.80	3.3	6.2	0.85	1.00	3.2	0
8	0.52	0.54	14.2	23.4	0.54	0.72	14.2	11.6
9	0.45	0.50	17.9	27.3	0.52	0.57	17.6	20.2
10	0.47	0.52	16.8	21.8	0.50	0.65	15.3	15.2
13	0.45	0.50	17.0	27.3	0.50	0.56	15.7	21.5
14	0.42	0.48	20.4	29.5	0.48	0.54	18.3	27.7
15	0.48	0.57	20.0	27.7	0.52	0.52	16.8	33.0
16	0.52	0.50	18.0	27.5	0.54	0.46	16.8	33.0
17	0.56	0.56	17.5	19.7	0.57	0.48	16.5	20.0
19	0.70	0.75	13.8	15.0	0.60	0.96	[illegible]	[illegible]

23	0.38	0.45	21.8	34.8	0.37	0.37	24.5	44.8
24	0.45	0.52	20.9	31.2	0.40	0.33	24.8	50.0
25	0.65	0.76	8.2	5.5	0.75	0.93	6.5	1.5
26	0.42	0.46	14.8	26.2	0.46	0.46	14.0	23.8
27	0.33	0.43	17.2	31.5	0.38	0.33	18.3	42.5
28	0.61	0.72	9.6	9.2	0.62	0.65	9.8	10.2
4/8	0.59	1.00	13.1	0	0.58	1.00	13.2	0
5	0.50	0.54	17.5	26.8	0.50	0.54	17.5	25.6
6	0.45	0.52	21.2	29.2	0.46	0.50	19.5	30.3
7	0.87	0.80	3.3	6.2	0.85	1.00	3.2	0
8	0.52	0.54	14.2	23.4	0.54	0.72	14.2	11.6
9	0.45	0.50	17.9	27.3	0.52	0.57	17.6	20.2
10	0.47	0.52	16.8	21.8	0.50	0.65	15.3	15.2
13	0.45	0.50	17.0	27.3	0.50	0.56	15.7	21.5
14	0.42	0.48	20.4	29.5	0.48	0.54	18.3	27.7
15	0.48	0.57	20.0	27.7	0.52	0.52	16.8	33.0
16	0.52	0.50	18.0	27.5	0.54	0.46	16.8	33.0
17	0.56	0.56	17.5	19.7	0.57	0.48	16.5	20.0
19	0.70	0.75	13.8	15.0	0.60	0.96	10.8	6.3
20	0.82	0.82	3.8	4.5	0.82	1.00	3.5	0
21	0.54	0.62	12.0	16.8	0.57	0.92	11.4	2.5
22	0.57	0.68	10.7	10.7	0.60	0.80	10.7	6.0
23	0.56	0.62	11.0	13.6	0.60	0.90	9.8	2.3
24	0.49	0.53	14.2	23.0	0.53	0.76	12.1	8.7
27	0.94	0.94	0.4	0.5	0.94	1.00	0.4	0
28	0.64	0.80	9.2	5.6	0.64	1.00	7.9	0
29	0.96	1.00	0.9	0	0.94	1.00	0.9	0
30	0.70	0.82	8.6	6.5	0.68	0.90	7.9	[illegible]
31	0.62	0.64	11.5	17.1	0.64	0.64	10.8	16.0

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2 FOLDOUT FRAME

Annex V

LIST OF VALUES USED IN PAR. 2.7

DATE	ET (mm/day)	Rn (mm/day)	$T_s - T_a$ (12-13 hr)	ET - R_n (mm/day)	ET_β (mm/hr)	Rn (mm/hr)	H_β (mm/hr)	u (m/s)	$f(u) = \frac{H}{T_s - T_a}$ $\times 10^{-3}$
15/7	5.2	5.6	8.2	- 0.4	0.66	0.85	0.20	3.8	24.9
16	4.5	5.6	10.3	- 1.1	0.62	0.78	0.16	1.9	15.5
17	5.5	6.9	10.6	- 1.4	0.68	0.81	0.13	2.7	12.3
20	3.3	3.2	6.5	+ 0.1	0.46	0.50	0.04	1.7	6.1
21	7.8	5.8	7.4	+ 2.0	0.78	0.90	0.12	5.8	16.7
22	5.7	5.5	3.6	+ 0.2	0.38	0.53	0.15	3.8	42.0
23	6.2	5.7	10.6	+ 0.5	0.78	0.87	0.09	1.6	8.5
24	5.5	5.6	9.5	- 0.1	0.79	0.87	0.08	1.4	8.5
25	2.0	1.4	1.5	+ 0.6	0.08	0.10	0.02	1.0	13.2
27	5.0	5.2	9.7	- 0.2	0.75	0.77	0.02	1.4	2.1
28	2.2	2.3	3.5	- 0.1	0.25	0.27	0.02	1.6	5.7
4/8	4.7	5.1	9.0	- 0.4	0.58	0.68	0.10	0.0	11.1
5	5.3	5.5	9.2	- 0.2	0.67	0.77	0.10	1.6	10.8
6	5.4	5.8	9.0	- 0.4	0.72	0.79	0.07	1.3	7.8
7	1.6	1.2	3.3	+ 0.4	0.09	0.10	0.01	1.3	3.0
8	4.5	5.5	9.4	- 1.0	0.69	0.83	0.14	2.2	14.9
9	5.2	5.5	8.9	- 0.3	0.67	0.78	0.11	1.9	12.4
10	4.0	5.2	6.6	- 1.2	0.57	0.80	0.23	3.8	34.8
13	4.3	4.9	10.3	- 0.6	0.62	0.76	0.14	2.1	13.5
14	4.9	5.4	9.2	- 0.5	0.65	0.76	0.11	1.6	11.9
15	4.3	4.7	9.6	- 0.4	0.63	0.74	0.11	1.0	11.4
17	3.9	4.4	3.3	- 0.5	0.21	0.22	0.01	1.6	3.0
19	3.1	3.2	9.8	- 0.1	0.65	0.79	0.14	1.0	14.3
20	1.3	1.4	2.6	- 0.1	0.11	0.12	0.01	1.5	3.9
21	4.3	5.2	9.2	- 0.9	0.62	0.78	0.16	1.7	17.4
22	3.7	3.7	4.0	0	0.25	0.26	0.01	1.2	2.5
23	3.8	4.7	5.8	- 0.9	0.52	0.79	0.27	5.0	47.0
24	4.2	4.7	8.8	- 0.5	0.64	0.76	0.12	2.2	13.6

4/8	4.7	5.1	9.0	- 0.4	0.58	0.68	0.10	0.0	11.1
5	5.3	5.5	9.2	- 0.2	0.67	0.77	0.10	1.6	10.8
6	5.4	5.8	9.0	- 0.4	0.72	0.79	0.07	1.3	7.8
7	1.6	1.2	3.3	+ 0.4	0.09	0.10	0.01	1.3	3.0
8	4.5	5.5	9.4	- 1.0	0.69	0.83	0.14	2.2	14.9
9	5.2	5.5	8.9	- 0.3	0.67	0.78	0.11	1.9	12.4
10	4.0	5.2	6.6	- 1.2	0.57	0.80	0.23	3.8	34.8
13	4.3	4.9	10.3	- 0.6	0.62	0.76	0.14	2.1	13.5
14	4.9	5.4	9.2	- 0.5	0.65	0.76	0.11	1.6	11.9
15	4.3	4.7	9.6	- 0.4	0.63	0.74	0.11	1.0	11.4
17	3.9	4.4	3.3	- 0.5	0.21	0.22	0.01	1.6	3.0
19	3.1	3.2	9.8	- 0.1	0.65	0.79	0.14	1.0	14.3
20	1.3	1.4	2.6	- 0.1	0.11	0.12	0.01	1.5	3.9
21	4.3	5.2	9.2	- 0.9	0.62	0.78	0.16	1.7	17.4
22	3.7	3.7	4.0	0	0.25	0.26	0.01	1.2	2.5
23	3.8	4.7	5.8	- 0.9	0.52	0.79	0.27	5.0	47.0
24	4.2	4.7	8.8	- 0.5	0.64	0.76	0.12	2.2	13.6
27	1.2	1.0	2.9	+ 0.2	0.12	0.17	0.05	2.6	17.3
28	2.9	3.5	2.7	- 0.6	0.38	0.48	0.10	3.7	38.0
29	1.6	1.9	1.9	- 0.3	0.06	0.09	0.03	1.1	15.8
30	2.8	3.3	4.1	- 0.5	0.28	0.31	0.03	1.1	7.3
31	4.1	4.9	7.2	- 0.8	0.55	0.64	0.09	1.3	12.5